Introduction

Newton's laws of motion describe the motion of the dolphin's path. (credit: Jin Jang)

Isaac Newton (1642–1727) was a natural philosopher; a great thinker who combined science and philosophy to try to explain the workings of nature on Earth and in the universe. His laws of motion were just one part of the

monumental work that has made him legendary. The development of Newton's laws marks the transition from the Renaissance period of history to the modern era. This transition was characterized by a revolutionary change in the way people thought about the physical universe. Drawing upon earlier work by scientists Galileo Galilei and Johannes Kepler, Newton's laws of motion allowed motion on Earth and in space to be predicted mathematically. In this chapter you will learn about force as well as Newton's first, second, and third laws of motion.

Force

Note:
SECTION LEARNING OBJECTIVES

By the end of this section, you will be able to:

- Differentiate between force, net force and dynamics
- Draw a free-body diagram
- Learn Newton’s 1st law: F_{net}

dynamics	external force	force
free body diagram	net external force	net force

Section Key Terms

Defining Force and *Dynamics*

Force is the cause of motion, and motion draws our attention. Motion itself can be beautiful, such as a dolphin jumping out of the water, the flight of a bird, or the orbit of a satellite. The study of motion is called kinematics, but kinematics only describes the way objects move—their velocity and their acceleration. **Dynamics** considers the forces that affect the motion of moving objects and systems. Newton’s laws of motion are the foundation of dynamics. These laws describe the way that objects speed up, slow down, stay in motion, and interact with other objects. They are also universal laws in that they apply everywhere on Earth as well as in space.

A force pushes or pulls an object. The object being moved by a force could be an inanimate object such as a table, or an animate object such as a person. The pushing or pulling may be done by a person, or even the gravitational pull of the earth. Forces have different magnitudes and directions; this means that some forces are stronger than others and can point in different directions. For example, a cannon exerts a strong force on the cannonball that is launched into the air. In contrast, a mosquito landing on your arm exerts only a small force on your arm.

Note:

A Note called Watch Physics with YouTube Embedded

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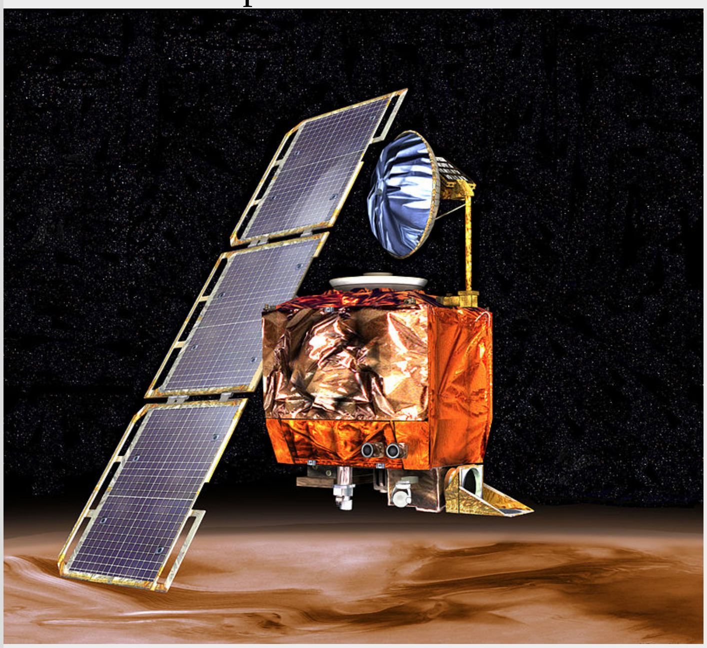
https://www.youtube.com/embed/40ETbLVkLKc

When multiple forces act on an object, the forces combine. Adding together all of the forces acting on an object gives the total, or **net force**. An **external force** is a force that acts on an object inside of the system from outside of the system. This is different than an internal force, which acts between objects that are both within the system. The **net external force** combines these two definitions; it is the total combined external force. We go into more detail about net force, external force, and net external force in the coming sections. In mathematical terms, two forces acting in opposite directions have opposite signs (positive or negative). By convention, the negative sign is assigned to movement to the left or downward. If two forces pushing in opposite directions are added together, the larger force will be somewhat canceled out by the smaller force pushing in the opposite direction. It is important to be consistent with your chosen coordinate system within a problem; for example, if negative values are assigned to the

downward direction for velocity, then distance, force and acceleration should also be designated as negative in the downward direction.

Note:
Mars Probe Explosion



Physicists make calculations all the time, but they do not always get the right answers. In 1998, NASA, The National Aeronautics and Space Administration (http://www.theguardian.com/technology/blog/2011/jul/13/technology-links-newsbucket), launched the Mars Climate Orbiter ([link]), a $125 million dollar satellite designed to monitor the Martian atmosphere. It was supposed to orbit the planet and take readings from a safe distance. The American scientists made calculations in English units (feet, inches, pounds . . .) and forgot to convert their answers to the standard Metric SI units. This was a very costly mistake. Instead of orbiting the planet as planned, the *Mars Climate Orbiter* ended up flying into the Martian atmosphere. The probe disintegrated. It was one of the biggest embarrassments in NASA's history. ([link]) shows the different ways the scientists tried to figure out the formula. They used $a \propto \frac{1}{m}$ and $F_{net} = 0$ or $\sum F = 0$

Here's list of some of the years of satellite launches:

- 1969

    a. January
    b. September
    c. November

- 1970
- 1985
- 2012

Exercise:

Problem:[link]

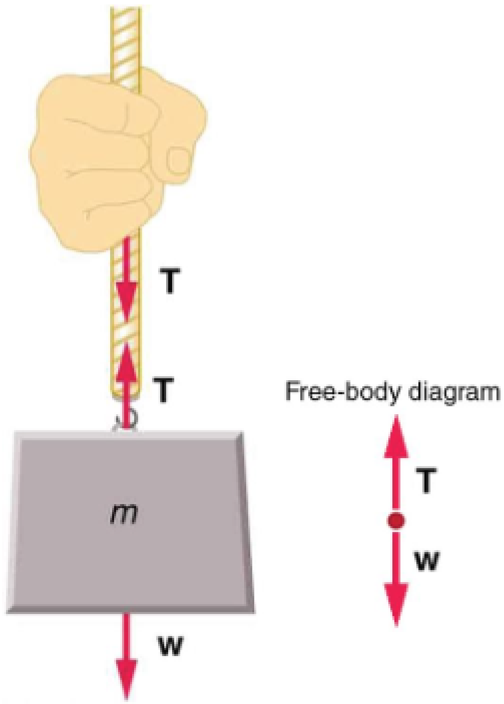
Free-body Diagrams and Examples of Forces

For our first example of force, consider an object hanging from a rope. This gives us the opportunity to introduce a useful tool known as a **free-body diagram**. A free-body diagram represents the object being acted upon (or free body) as a single point. Only the forces acting on the body (that is, external forces) are shown and are represented by vectors (which are drawn as arrows). These forces are the only ones shown because only external forces acting on the body affect its motion. We can ignore any internal forces within the body because they cancel each other out, as Newton's third law will show. Free-body diagrams are very useful for analyzing forces acting on an object.

Here are some things included in a free-body diagram:

a. Forces
    - Internal
    - External
    - Net

b. Vectors
c. Arrows
d. Equation



An object of mass m held up by the force of tension.

[link] shows the force of tension acting in the upward direction, opposite the force of gravity. These forces are indicated in the free-body diagram by an arrow pointing up, representing tension, and another arrow pointing down, representing gravity. In a free-body diagram, the lengths of the arrows show the relative magnitude (or strength) of the forces. Since forces are vectors, they add just like other vectors. Notice that the two arrows have equal lengths in [link], which means that the forces of tension and weight are of equal magnitude. Since these forces of equal magnitude act in

opposite directions, they are perfectly balanced, so they add together to give a net force of zero.

Not all forces are as noticeable as when you push or pull on something. Some forces act without physical contact, such as the pull of a magnet in the case of magnetic force or the gravitational pull of the earth in the case of gravitational force.

In the next three sections on Newton’s laws of motion, we will learn about three specific types of forces—friction, the normal force, and the gravitational force. To analyze situations involving forces, we will create free-body diagrams to organize the framework of the mathematics for each individual situation.

Note: Correctly drawing and labeling a free-body diagram is an important first step for solving a problem. It will help you visualize the problem and correctly apply the mathematics to solve the problem.

Section Summary

- Dynamics is the study of how forces affect the motion of objects such as:
    - Pushes
    - Pulls
- Force is a push or pull that can be defined in terms of various *standards*. It is a vector and so has both magnitude and direction.
- External forces are any forces from outside of a body that act on the body. A free-body diagram is a drawing of all external forces acting on a body.

Key Equations

Equation:

$$F_{\text{net}} = 0(\text{or} \sum F = 0$$

Equation:

$$\text{a} \propto \frac{1}{m}$$

Check Your Understanding

Exercise:

Problem:[link]

Exercise:

Problem:[link]

Exercise:

Problem:[link]

Exercise:

Problem:[link]

Concept Items

Exercise:

Problem:[link]

Exercise:

Problem:[link]

Critical Thinking Items

Exercise:

Problem:[link]

Exercise:

Problem:[link]

Test Prep Multiple Choice

Exercise:

Problem:[link]

Exercise:

Problem:[link]

Test Prep Short Answer

Exercise:

Problem:[link]

Exercise:

Problem:[link]

Exercise:

Problem:[link]

Exercise:

Problem:[link]

Test Prep Extended Response

Exercise:

Problem:[link]

Exercise:

Problem:[link]

Glossary

dynamics
: the study of how forces affect the motion of objects and systems

external force
: a force acting on an object or system that originates outside of the object or system

force
: a push or pull on an object with a specific magnitude and direction; can be represented by vectors; can be expressed as a multiple of a standard force

free-body diagram
: a diagram showing all external forces acting on a body

net external force
: the sum of all external forces acting on an object or *system*

net force
: the sum of all forces acting on an object or system

Newton's First Law of Motion: Inertia

Note:

SECTION LEARNING OBJECTIVES

By the end of this section you will be able to:

- Describe Newton's first law and friction $a \propto \frac{1}{m}$
- Discuss the relationship between mass and inertia

friction	inertia	law of inertia
mass	Newton's first law of motion	system

Section Key Terms

Newton's First Law and Friction

Newton's first law of motion states that:

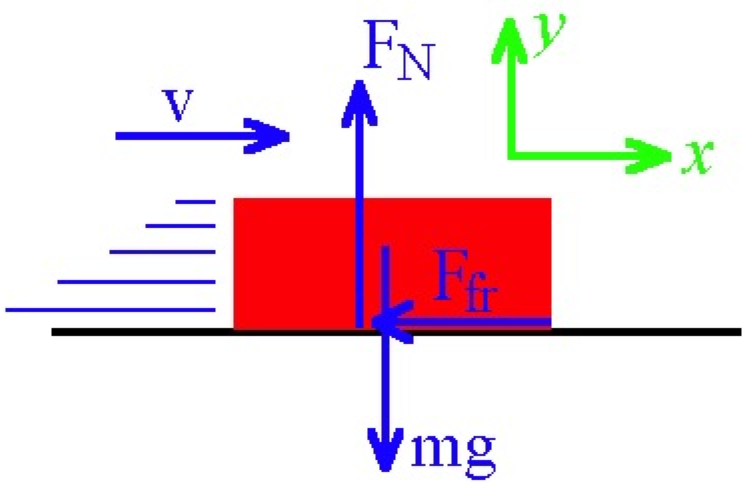
1. A body at rest tends to stay at rest $a \propto \frac{1}{m}$
2. A body in motion tends to remain in motion at constant velocity unless acted on by a net external force (recall that “constant velocity” means in a straight line and at constant speed). $F_{net} = 0$ or $(\sum F = 0)$

Newton's 1st Law: $F_{net} = 0$ **or** $(\sum F = 0)$

At first glance, this law may seem to contradict your everyday experience. You have probably noticed that a moving object will usually slow down and stop unless some effort is made to keep it moving. The key to understanding why, for example, a sliding box slows down (seemingly on its own) is that a net external force acts on it to make it slow down. Without this net external force, the box would continue to slide at a constant velocity (as stated in Newton’s first law of motion). What force acts on the box to slow it down? It is called **friction**. Friction is an external force that acts opposite to the direction of motion (see [link]). Think of it as a resistance to motion that slows things down.

Friction:

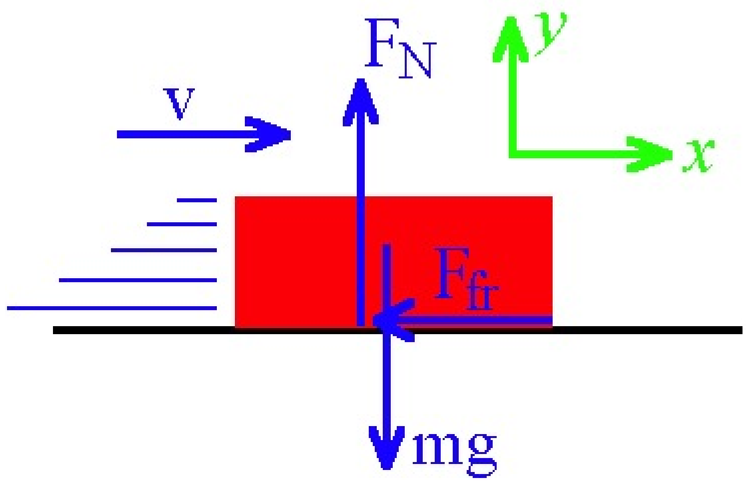
1. Goes in the opposite direction



2. Causes an object to slow down ([link])

Consider an air hockey table. When the air is turned off, the puck slides only a short distance before friction slows it to a stop. However, when the air is turned on, it lifts the puck slightly so that the puck experiences very little friction as it moves over the surface. With friction almost eliminated, the puck glides along with very little change in speed. On a frictionless surface, the puck would experience no net external force (ignoring air resistance, which is also a form of friction). Additionally, if we know enough about friction, we can accurately predict how quickly objects will slow down.

Now let’s think about another example. A man pushes a box across a floor at constant velocity by applying a force of +50 N (the positive sign indicates by convention that the direction of motion is to the right). What is the force of friction that opposes the motion? The force of friction must be −50 N. Why? According to Newton’s first law of motion, any object moving at constant velocity has no net external force acting upon it, which means that the sum of the forces acting on the object must be zero. The mathematical way to say that no net external force acts on an object is $F_{net} = 0$, or $\sum F = 0$. So if the man applies +50 N of force, then the force of friction must be −50 N for the two forces to add up to zero (i.e., “cancel” each other). Whenever you encounter the phrase “at constant velocity,” Newton’s first law tells you that the net external force is zero.



For a box sliding across a floor, friction acts in the direction opposite to the velocity.

The force of friction depends on two things: the coefficient of friction and the normal force. The coefficient of friction is a constant that depends on the nature of the surfaces in contact with one another. The normal force is

the force exerted by a surface that pushes on an object in response to gravity pulling the object down. In equation form, the force of friction is

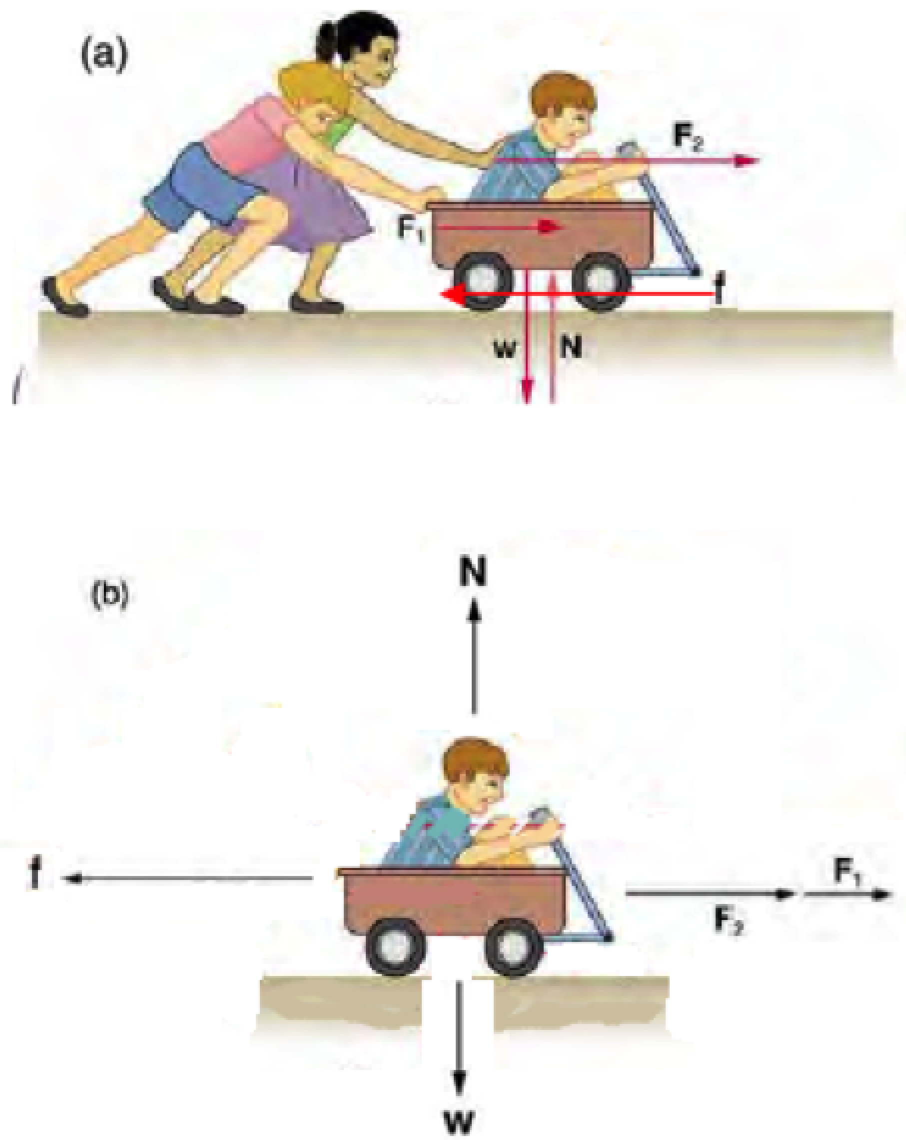
Equation:

$$f = \mu N$$

where μ is the coefficient of friction and N is the normal force. The coefficient of friction is discussed in more detail in the next chapter and the normal force is discussed in more detail in section four of this chapter.

Recall from section one that a net external force acts from outside on the object of interest. A more precise definition is that it acts on the **system** of interest. A system is one or more objects that you choose to study. It is important to define the system at the beginning of a problem to figure out which forces are external and need to be considered and which are internal and can be ignored.

For example, in [link] (a), two children push a third child in a wagon at constant velocity. The system of interest is the wagon plus the small child shown in part b of the figure. The two children behind the wagon exert external forces on this system (F_1, F_2). Friction f acting at the axles of the wheels and at the surface where the wheels touch the ground is another external force acting on the system. Two more external forces act on the system: the weight W of the system pulling down and the normal force N of the ground pushing up. Notice that the wagon is not accelerating vertically, so Newton’s first law tells us that the normal force balances the weight. Because the wagon is moving forward at constant velocity, then the force of friction must have the same strength as the sum of the forces applied by the two children.



(a) The wagon and rider form a “system” that is acted on by external forces. (b)The two children pushing the wagon and child provide two external forces. Friction acting at the wheel axles and on the surface of the tires where they touch the ground provides an external force that acts against the direction of motion. The weight *W* and the normal force *N* from the ground are two more external forces acting on the system. All external forces are represented in the figure by arrows. All of the external forces acting on the system add together, but because the

wagon moves at a constant velocity, all the forces must add up to zero.

Mass and Inertia

Inertia is the tendency for an object at rest to remain at rest or for a moving object to remain in motion in a straight line with constant speed. This key property of objects was first described by Galileo. Later, Newton incorporated the concept of inertia into his first law, which is often referred to as the **law of inertia**.

As we know from experience, some objects have more inertia than others. For example, changing the motion of a large truck is more difficult than changing the motion of a toy truck. In fact, the inertia of an object is proportional to the mass of the object. **Mass** is a measure of the amount of matter (or "stuff") in something. The quantity or amount of matter in an object is determined by the number and type of atoms it contains. Unlike weight (which changes if the gravitational force changes), mass does not depend on gravity. The mass of an object is the same on Earth, in orbit, or on the surface of the Moon. In practice, it is very difficult to count and identify all of the atoms and molecules in an object, so mass is usually not determined this way. Instead, the mass of an object is determined by comparing it with the standard kilogram. Mass is therefore expressed in kilograms.

Note: In everyday language, people often use the terms weight and mass interchangeably—but this is not correct. Weight is actually a force (we cover this in more detail in section three).

Note:

Newton’s first law of motion

This video contrasts the way we thought about motion and force in the time before Galileo’s concept of inertia and **Newton’s first law of motion** with the way we understand force and motion now. Refer to [link] as you watch.

https://www.khanacademy.org/embed_video?v=5-ZFOhHQS68

1. Galileo’s concepts
   a. Things just come to a stop
   b. Forces don’t act against objects
2. Newton’s concepts
   a. Objects will continue at the same speed if no opposing force
   b. Weight is a force acting against an object.

Exercise:

Problem: [link]

Note:

Forces and Motion: Basics

In this simulation, you will first explore net force by placing blue people on the left side of a tug of war rope and red people on the right side of the rope (by clicking people and dragging them with your mouse). Experiment with changing the number and size of people on each side to see how it affects the outcome of the match and the net force. Hit the Go! button to start the match, and the “reset all” button to start over.

a. The side with the most force wins
b. The bigger the difference in the force, the easier it is for one side to win.
c. When force is equal, no one wins.

Next, click on the Friction tab. Try selecting different objects for the person to push. Slide the applied force button to the right to apply force to the right and to the left to apply force to the left. The force will continue to be applied as long as you hold the button down. See the arrow representing friction change in magnitude and direction depending on how much force you apply. Try increasing or decreasing the friction force to see how this affects the motion.
http://archive.cnx.org/specials/eb99fecc-0e7a-4c09-86e2-8bcb1490c0d3/energy-forms-and-changes/

Exercise:

Problem: [link]

Section Summary

- Newton’s first law states that a body at rest remains at rest or, if moving, remains in motion in a straight line at a constant speed unless acted on by a net external force. This is also known as the law of inertia.
- Inertia is the tendency of an object at rest to remain at rest or, if moving, to remain in motion at constant velocity. Inertia is related to an object’s mass.
- Friction is a force that opposes motion and causes an object or system to slow down.
- Mass is the quantity of matter in a substance.

Key Equations

Equation:

Newton's first law

$$f\left(x\right)=\text{c, where c is a constant}$$

Equation:

Newton's sixth law

$$f\left(x\right)=x$$

Check Your Understanding

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Exercise:

Problem:[link]

Exercise:

Problem:[link]

Concept Items

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Critical Thinking Items

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Test Prep Multiple Choice

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Test Prep Short Answer

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Test Prep Extended Response

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Glossary

friction
: an external force that acts in the direction opposite to the direction of motion

inertia
: the tendency of an object at rest to remain at rest or for a moving object to remain in motion in a straight line and at constant speed—MATH

law of inertia
: Newton’s first law of motion: a body at rest remains at rest or, if in motion, remains in motion at a constant speed in a straight line unless acted on by a net external force; also known as the law of inertia

mass
: the quantity of matter in a substance; measured in kilograms

Newton's first law of motion
: a body at rest remains at rest or, if in motion, remains in motion at a constant speed in a straight line unless acted on by a net external force; also known as the law of inertia

system
: one or more objects of interest for which only the forces acting on them from the outside are considered but not the forces acting between

them or inside of them

Newton's Second Law of Motion

Note:

SECTION LEARNING OBJECTIVES

By the end of this section, you will be able to:

- Describe Newton's Second Law both verbally and mathematically
- Use Newton's Second Law to solve problems

freefall	Newton's second law of motion	weight

Section Key Terms

Describing Newton's Second Law of Motion

Newton’s first law considered bodies at rest or bodies in motion at constant velocity. The other state of motion to consider is when an object is moving with a changing velocity, which means a change in either the speed and/or the direction of motion. This type of motion is addressed by **Newton’s second law of motion**, which states how force causes changes in motion. Newton’s second law of motion is used to calculate what happens in situations involving forces and motion, and it shows the mathematical relationship between force, mass, and acceleration. Mathematically, the second law is most often written as

Equation:

$$F_{net} = ma$$

where F_{net} (or $\sum F$) is the net external force, m is the mass of the system, and a is the acceleration. Note that F_{net} and $\sum F$ are the same because the net external force is the sum of all of the external forces acting on the system.

First, what do we mean by “a change in motion”? A change in motion is simply a change in velocity: the velocity of an object can get bigger or smaller, its direction can change, or both. A change in velocity means, by definition, that an acceleration has occurred. Newton’s first law says that only a nonzero net external force can cause a change in motion, so a net external force must cause an acceleration. Note that “acceleration” can refer to slowing down or to speeding up. Acceleration can also refer to a change in the direction of motion with no change in speed, because acceleration is the change in velocity divided by the time it takes for that change to occur, and velocity is defined by speed and direction.

The equation $F_{net} = ma$ or $\sum F = ma$can be used for:

a. Speed

1. $a = \frac{F_{net}}{m}$ or $a = \frac{\sum F}{m}$
2. $a \propto F_{net}$

b. Direction

c. Velocity

From the equation F_{net}=ma, we see that force is directly proportional to both mass and acceleration, which makes sense. To accelerate two objects from rest to the same velocity, you would expect more force to be required to accelerate the more massive object. Likewise, for two objects of the same mass, applying a greater force to one would accelerate it to a greater velocity.

Now, let’s rearrange Newton’s second law to solve for acceleration. We get
Equation:

$$a = \frac{F_{net}}{m} \; or \;\; a = \frac{\sum F}{m}$$

In this form, it’s clear that acceleration is directly proportional to force, which we write as
Equation:

$$a \propto F$$

where the symbol SYMBOL means “proportional to.”

This proportionality states mathematically what we just said in words—acceleration is directly proportional to the net external force. When two variables are directly proportional to each other, then if one variable doubles, the other variable must double. Likewise, if one variable is reduced by half, the other variable must also be reduced by half. In general, when one variable is multiplied by a number, the other variable will also be multiplied by the same number. It seems reasonable that the acceleration of a system should be directly proportional to and in the same direction as the net external force acting on the system. An object experiences greater acceleration when acted on by a greater force.

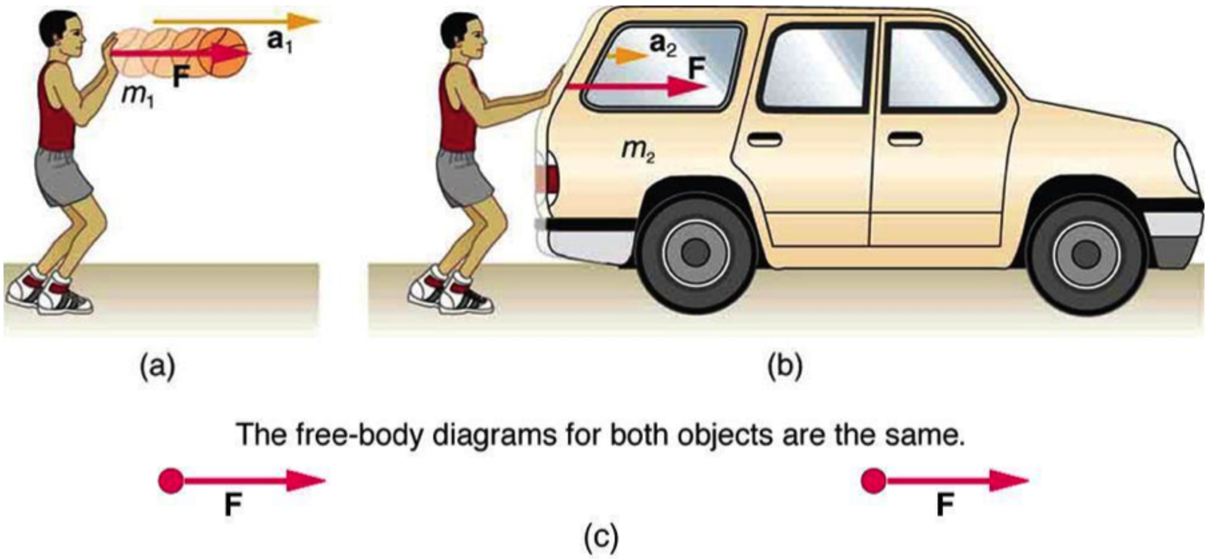
It is also clear from the equation $a = F_{net}/m$ that acceleration is inversely proportional to mass, which we write as
Equation:

$$a \propto \frac{1}{m}$$

Inversely proportional means that, if one variable is multiplied by a number, the other variable must be divided by the same number. Now, it also seems reasonable that acceleration should be inversely proportional to the mass of the system. In other words, the larger the mass (the inertia), the smaller the acceleration produced by a given force. This is illustrated in Figure 04_03_basketball, which shows that a given net external force applied to a basketball produces a much greater acceleration than when applied to a car.

Forces	**Equations**
Newton's second law of motion	$\mathbf{F}_{\text{net}} = m\mathbf{a}$
acceleration	• $\mathbf{a} = \frac{\mathbf{F}_{\text{net}}}{m}$ or $\mathbf{a} = \frac{\Sigma\mathbf{F}}{m}$ • $\mathbf{a} \propto \mathbf{F}_{\text{net}}$
mass	$a \propto \frac{1}{m}$

Section testing tableUse this table to find the different equations provided in this section.



A boy pushing a basketball and an SUV, demonstrating the inverse relationship between acceleration and mass

The same force exerted on systems of different mass produces different accelerations. (a) A boy pushes a basketball to make a pass. The effect of gravity on the ball is ignored. (b) The same boy pushing with identical force on a stalled car produces a far smaller acceleration (friction is negligible). Note that the free-body diagrams for the ball and for the car are identical, which allows us to compare the two situations.

Applying Newton's Second Law

Before putting Newton's second law into action, it is important to consider units. The equation $F_{net} = ma$ is used to define the units of force in terms of the three basic units of mass, length, and time (recall that acceleration has units of length divided by time squared). The SI unit of force is called the **newton** (abbreviated N) and is the force needed to accelerate a 1 kg system at the rate of 1 m/s^2. That is, because $F_{net} = ma$, we have
Equation:

$$1N = 1kg{*}1m/s^2 = 1\frac{kg \cdot m}{s^2}$$

One of the most important applications of Newton's second law is to calculate **weight** (also known as the gravitational force), which is usually represented mathematically as ***W***. When people talk about gravity, they don't always realize that it is an acceleration. When an object is dropped, it accelerates toward the center of Earth. Newton's second law states that the net external force acting on an object is responsible for the acceleration of the object. If air resistance is negligible, the net external force on a falling object is only the gravitational force (i.e., the weight of the object).

Weight can be represented by a vector because it has a direction. Down is defined as the direction in which gravity pulls, so weight is normally considered a downward force. By using Newton's second law, we can figure out the equation for weight.

Consider an object with mass *m* falling toward Earth. It experiences only the force of gravity (i.e. the gravitational force or weight), which is represented by **W**. Newton's second law states that $F_{net} = ma$. Since the only force acting on the object is the gravitational force, we have $F_{net} = W$. We know that the acceleration of an object due to gravity is *g*, so we have $a = g$. Substituting these two expressions into Newton's second law gives
Equation:

$$W = mg$$

This is the equation for weight—the gravitational force on a mass *m*. On Earth,$g = 9.80 m/s^2$, so the weight (disregarding for now the direction of the weight) of a 1.0 kg object on Earth is
Equation:

$$W = mg = \left(1.0 kg\right)\left(9.80\ m/s^2\right) = 9.8 N$$

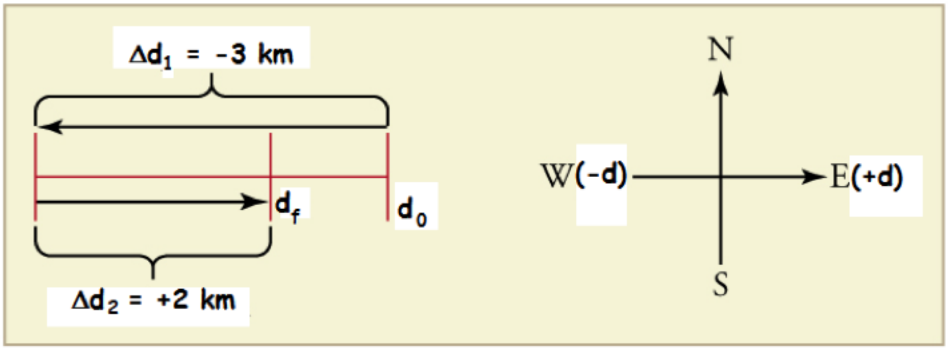
Although most of the world uses newtons as the unit of force, in the United States the most familiar unit of force is the pound (lb), where 1 N = 0.225 lb.

Recall that, although gravity acts downward, it can be assigned a positive or negative value, depending on the positive direction in your chosen coordinate system. Be sure to take this into consideration when solving problems with weight. When the downward direction is taken to be negative, as is often the case, acceleration due to gravity becomes $g = -9.8\ m/s^2$.

When the net external force on an object is its weight, we say that it is in **freefall**. In this case, the only force acting on the object is the force of gravity. On the surface of Earth, when objects fall downward toward Earth, they are never truly in freefall because there is always some upward force due to the air resistance that acts on the object (and there is also the buoyancy force of air, which is similar to the buoyancy force in water that keeps boats afloat).

Gravity varies slightly over the surface of Earth, so that the weight of an object depends very slightly on its location on Earth. Weight varies dramatically away from Earth's surface. On the Moon, for example, the acceleration due to gravity is only $1.67\ m/s^2$. Because weight depends on the force of gravity, a 1.0 kg mass weighs 9.8 N on Earth and only about 1.7 N on the Moon. It is important to remember that weight and mass are very different, although they are closely related. Mass is the quantity of matter (how much "stuff") in an object and does not vary, but weight is the gravitational force on an object and is proportional to the force of gravity. It is easy to confuse the two, because our experience is confined to Earth, and the weight of an object is essentially the same no matter where you are on Earth. Adding to the confusion, the terms mass and weight are often used interchangeably in everyday language; for example, our medical records often show our "weight" in kilograms, but never in the correct units of newtons.

Note:
Mass and Weight
In this activity you will use a scale to investigate mass and weight.



Materials

- 1 scale
- 1 table ([link])

Safety Warning

- Organisms: This lab uses organisms that can pass on diseases.

1. What do bathroom scales measure?
2. When you stand on a bathroom scale, what happens to the scale? It depresses slightly. The scale contains springs that compress in proportion to your weight—similar to rubber bands expanding when pulled. **Newton's 1st law**: $F_{net} = 0 \; or \; (\sum F = 0)$
3. The springs provide a measure of your weight (provided you are not accelerating). This is a force in newtons (or pounds). In most countries, the measurement is now divided by 9.80 to give a reading in kilograms, which are units of mass. The scale detects weight but is calibrated to display mass.
4. If you went to the Moon and stood on your scale, would it detect the same "mass" as it did on Earth? How about:

   a. Mars
   b. Venus
   c. Saturn

Planet	**Mass**	**Weight:** $(F_{net} = 0 \; or \; (\sum F = 0))$
Mars	12 kg	5N
Venus	20 kg	90N
Saturn	1 kg	13N

This table shows the differences in mass and weights on different planets.

Exercise:

Problem: [link]

Note: Only *net external force* impacts the acceleration of an object. If more than one force acts on an object and you calculate the acceleration by using only one of these forces, you will not get the correct acceleration for the object.

Note:
Newton's second law of motion
This video reviews Newton's second law of motion $(F_{net} = 0 \; or \; (\sum F = 0))$ and how net external force and acceleration relate to one another and to mass. It also covers units of force, mass, and acceleration and goes over a sample problem.
https://www.khanacademy.org/embed_video?v=ou9YMWlJgkE
Newton's other laws:

- Newton's first law of motion
- Newton's third law of motion

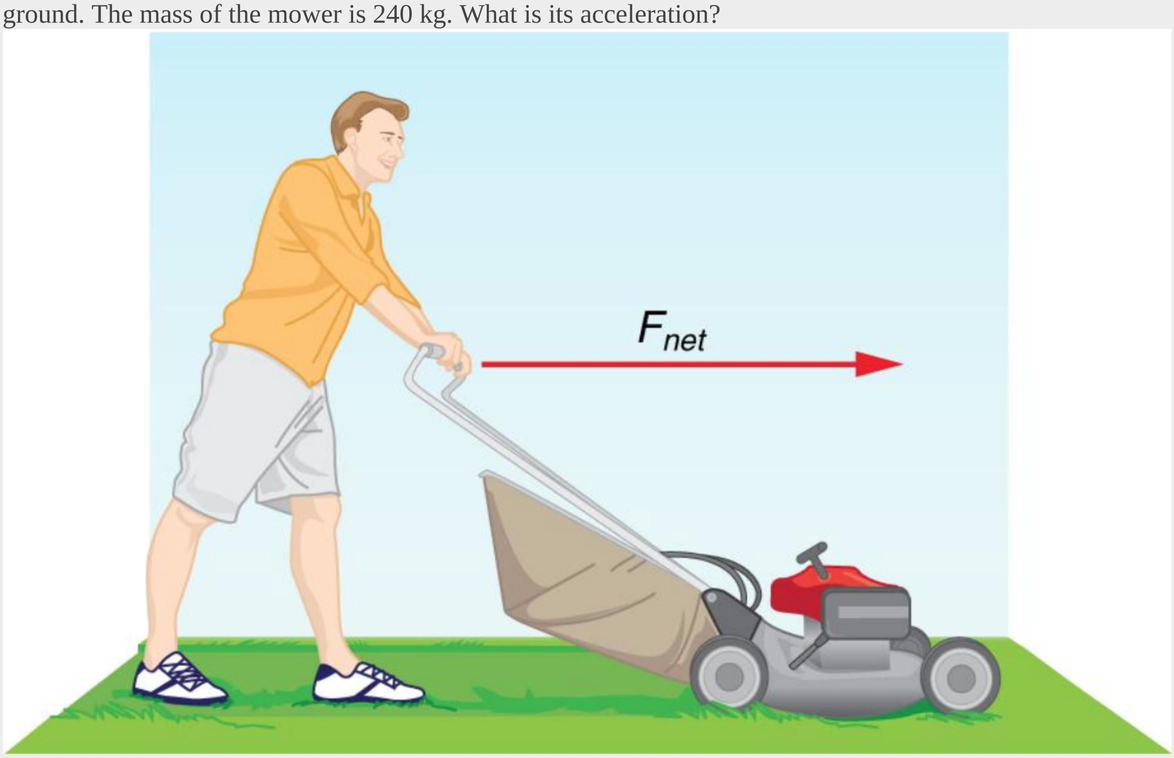
Exercise:

Problem: [link]

Note:
Exercise:
What Acceleration Can a Person Produce when Pushing a Lawn Mower?

Problem:

Suppose that the net external force (push minus friction) exerted on a lawn mower is 51 N parallel to the ground. The mass of the mower is 240 kg. What is its acceleration?



Note:
Strategy
Since F_{net} and m are given, the acceleration can be calculated directly from Newton's second law: $F_{net} = ma$.

Solution:

Solving Newton's second law for the acceleration, we find that the magnitude of the acceleration, a, is $a = \frac{F_{net}}{m}$. Entering the given values for net external force and mass gives $a = \frac{51N}{240kg}$. Inserting the units $kg \cdot m/s^2$ for N yields $a = \frac{51\,kg \cdot m/s^2}{240\,kg} = 0.21\ m/s^2$.

Discussion

Note:

- Correctly drawing and labeling a free-body diagram is an important first step for solving a problem.
  1. What needs to be labeled?
     a. List three answers
     b. Describe how you would label those three answers
  2. How do you check to make sure that a diagram is correct?
- Newton's 1st law: $F_{net} = 0$

The acceleration is in the same direction as the net external force, which is parallel to the ground and to the right. There is no information given in this example about the individual external forces acting on the system, but we can say something about their relative magnitudes. For example, the force exerted by the person pushing the mower must be greater than the friction opposing the motion because we are given that the net external force is in the direction in which the person pushes. Also, the vertical forces must cancel if there is no acceleration in the vertical direction (the mower is moving only horizontally). The acceleration found is reasonable for a person pushing a mower; the mower's speed must increase by 0.21 m/s every second, which is possible. The time during which mower accelerates would not be very long because the person's top speed would soon be reached. At this point, the person could push a little less hard, because he only has to overcome friction.
Exercise:
What Rocket Thrust Accelerates This Sled?

Problem:

Prior to manned space flights, rocket sleds were used to test aircraft, missile equipment, and physiological effects on humans at high accelerations. Rocket sleds consisted of a platform mounted on one or two rails and propelled by several rockets.

Calculate the magnitude of force exerted by each rocket, called its thrust T, for the four-rocket propulsion system shown below. The sled's initial acceleration is 49 m/s2, the mass of the system is 2100 kg, and the force of friction opposing the motion is 650 N.

Types of Links	URLs
External link	http://upload.wikimedia.org/wikipedia/commons/0/00/Herrenhaustag_MI_Juni_2009_205.jpg
Internal link	http://cnx.org/contents/b3c1e1d2-839c-42b0-a314-e119a8aafbdd@8.53:49/Concepts_of_Biology

Sample problem testing table

Note:
Strategy
The system of interest is the rocket sled. Although forces act vertically on the system, they must cancel because the system does not accelerate vertically. This leaves us with only horizontal forces to consider. We'll assign the direction to the right as the positive direction. See the free-body diagram in the figure.

Solution:

We start with Newton's second law and look for ways to find the thrust **T** of the engines. Because all forces and acceleration are along a line, we need only consider the magnitudes of these quantities in the calculations. We begin with
Equation:

$$F_{net} = ma$$

where F_{net} is the net external force in the horizontal direction. We can see from the image above that the engine thrusts are in the same direction (which we call the positive direction), whereas friction opposes the thrust. In equation form, the net external force is
Equation:

$$F_{net} = 4T - f$$

- Newton's second law tells us that $F_{net} = ma$, so we get
- $ma = 4T - f$
- After a little algebra we solve for the total thrust 4T:
- $4T = ma + f$
- which means that the individual thrust is
- $T = \frac{ma+f}{4}$
- Inserting the known values yields
- $T = \frac{(2100kg)(49\,m/s^2)+650N}{4} = 2.6*10^4N$

Discussion

The numbers are quite large, so the result might surprise you. Experiments such as this were performed in the early 1960s to test the limits of human endurance and to test the apparatus designed to protect fighter pilots in emergency ejections. Speeds of 1000 km/h were obtained, with accelerations of 45g. (Recall that g, the acceleration due to gravity, is $9.8\ m/s^2$. An acceleration 45g is 45*$9.8\ m/s^2$, which is approximately 440 m/s^2

.) Living subjects are no longer used, and land speeds of 10,000 km/h have now been obtained with rocket sleds. In this example, as in the preceding example, the system of interest is clear. We will see in later examples that choosing the system of interest is crucial—and that the choice is not always obvious.

Practice Problems

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Note:
Ptolemy vs. Copernicus
Before the discoveries of Kepler, Copernicus, Galileo, Newton, and others, the solar system was thought to revolve around Earth as shown in Figure 04_03_solar_img (a). This is called the Ptolemaic (the P is silent) view, for the Greek philosopher who lived in the second century AD. This model is characterized by a list of facts for the motions of planets with no cause and effect explanation. There tended to be a different rule for each heavenly body and a general lack of simplicity.
Figure 04_03_solar_img (b) represents the modern or **Copernican model**. In this model, a small set of rules and a single underlying force explain not only all motions in the solar system, but all other situations involving gravity. The breadth and simplicity of the laws of physics are compelling. As our knowledge of nature has grown, the basic simplicity of its laws has become ever more evident.
Nicolaus Copernicus (1473 – 1543) first had the idea that the planets circle the Sun about 1514. It took him almost 20 years to work out the mathematical details for his model. He waited another 10 years or so to publish his work. It is thought he hesitated because he was afraid people would make fun of his theory. Actually, the reaction of many people was more one of fear and anger. Many people felt the Copernican model threatened their basic belief system. About 100 years later, the astronomer Galileo Galilei was arrested and put under house arrest for saying he thought the Earth traveled around the Sun. In all, it took almost 300 years for everyone to admit that Nicolaus had been right all along.
Astronomers:

1. Copernicus
   a. Planets circle the Sun
   b. Didn't share his ideas out of fear
2. Galileo
   a. 100 years later
   b. Put in prison

Exercise:

Problem: [link]

Section Summary

- Acceleration is a change in velocity, meaning a change in speed, direction, or both.
- An external force acts on a system from outside the system, as opposed to internal forces, which act between components within the system.
- Newton’s second law of motion states that the acceleration of a system is directly proportional to and in the same direction as the net external force acting on the system, and inversely proportional to the system’s mass.
- In equation form, Newton’s second law of motion is $F_{net} = ma$ or $\sum F = ma$. This is sometimes written as $a = \frac{F_{net}}{m} \;\; or \;\; a = \frac{\sum F}{m}$.
- The weight of an object of mass m is the force of gravity that acts on it. From Newton’s second law, weight is given by $W = mg$

Key Equations

Equation:

Newton's Second Law of Motion

$$F_{net} = ma \;\; or \;\; \sum F = ma$$

Equation:

Solving for acceleration

$$a = \frac{F_{net}}{m} \;\; or \;\; a = \frac{\sum F}{m}$$

Equation:

Solving for weight

$$W = mg$$

Check Your Understanding

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Concept Items

Exercise:

Problem: [link]

Critical Thinking Items

Exercise:

Problem: [link]

Test Prep Multiple Choice

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Test Prep Short Answer

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Extended Response

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Glossary

freefall
: a situation in which the only force acting on an object is the force of gravity (Fnet = 0 (or ∑F = 03)

Newton's second law of motion
: the net external force F_{net} on an object is proportional to and in the same direction as the acceleration of the object, a, and also proportional to the object's mass m; defined mathematically as Fnet = ma or $\sum F = ma$

weight
: the force of gravity, **W**, acting on an object of mass m; defined mathematically as **W** = m**g**, where g is the magnitude and direction of the acceleration due to gravity

Newton's Third Law of Motion

Note:
SECTION LEARNING OBJECTIVES

By the end of this section, you will be able to:

- Describe Newton's Third Law both verbally and mathematically
- Use Newton's Third Law to solve problems

Newton's third law of motion	normal force	tension	thrust

Section Key Terms

Describing Newton’s Third Law of Motion

If you have ever stubbed your toe, you have noticed that although your toe initiates the impact, the surface that you stub it on exerts a force back on your toe. Although the first thought that crosses your mind is probably “ouch, that hurt” rather than “this is a great example of Newton’s third law,” both statements are true.

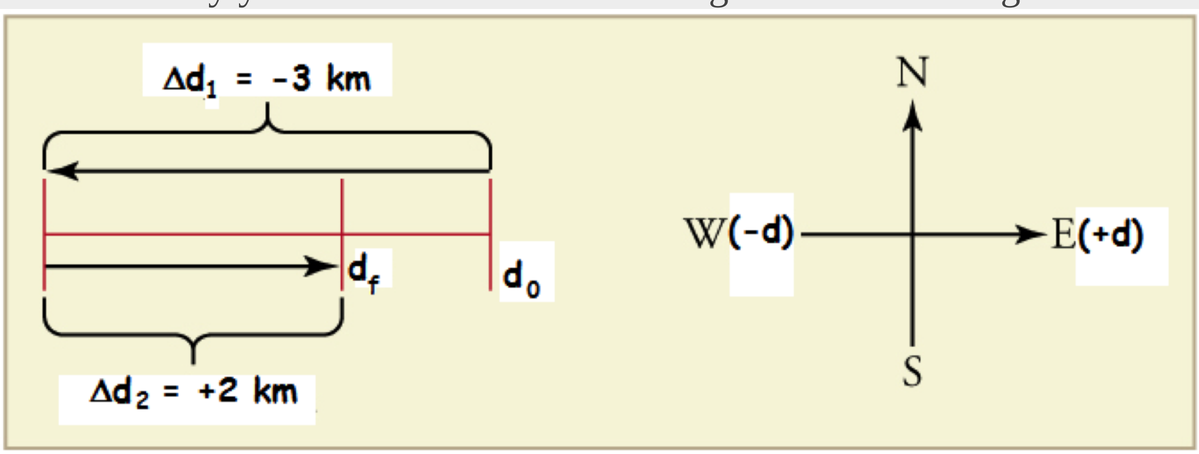
This is exactly what happens whenever one object exerts a force on another—each object experiences a force that is the same strength as the force acting on the other object but that acts in the opposite direction. Everyday experiences, such as stubbing a toe or throwing a ball, are all perfect examples of Newton’s third law in action.

Newton’s third law of motion states that, whenever a first object exerts a force on a second object, the first object experiences a force equal in magnitude but opposite in direction to the force that it exerts

Newton’s third law of motion tells us that forces always occur in pairs, and one object cannot exert a force on another without experiencing the same strength force in return. We sometimes refer to these force pairs as “action-reaction” pairs, where the force exerted is the action, and the force experienced in return is the reaction (although which is which depends on your point of view).

Newton’s third law is useful for figuring out which forces are external to a system. Recall that identifying external forces is important when setting up a problem, because the external forces must be added together to find the net force.

Note:
Mass and Weight
In this activity you will use a scale to investigate mass and weight.



Materials

- 1 scale
- 1 table

Safety Warning

- Organisms: This lab uses organisms that can pass on diseases.

1. What do bathroom scales measure?
2. When you stand on a bathroom scale, what happens to the scale? It depresses slightly. The scale contains springs that compress in proportion to your weight—similar to rubber bands expanding when pulled. Newton's 1st law: Fnet = 0 or (or ∑F = 01)
3. The springs provide a measure of your weight (provided you are not accelerating). This is a force in newtons (or pounds). In most countries, the measurement is now divided by 9.80 to give a reading in kilograms, which are units of mass. The scale detects weight but is calibrated to display mass.
4. If you went to the Moon and stood on your scale, would it detect the same "mass" as it did on Earth? How about: a. mars b. venus c.saturn

Planet	Mass	Weight (Fnet = 0 or (or ∑F = 01)
Mars	12kg	5N
Venus	20kg	90N
Saturn	1kg	13N

Table 3: Snap lab testing table

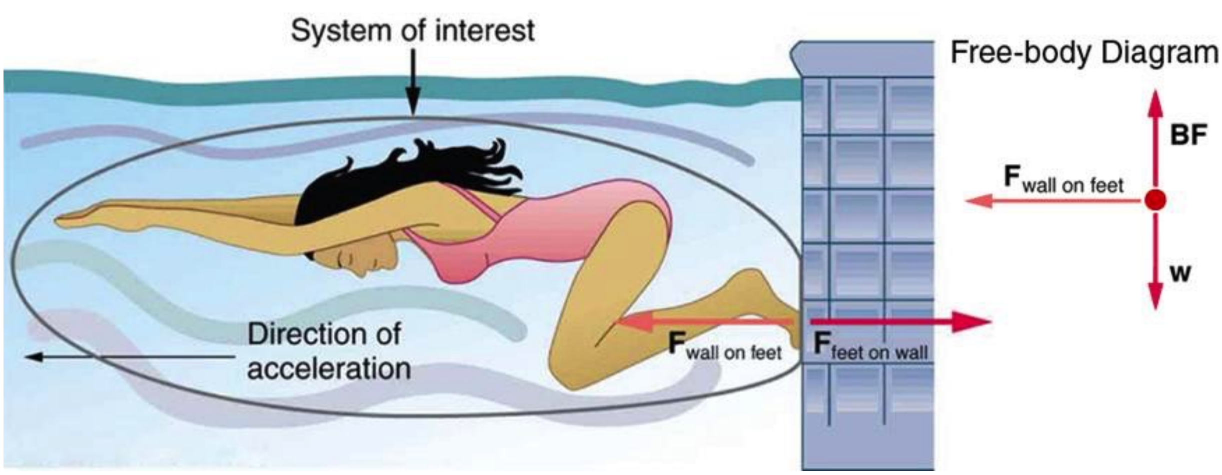
Exercise:

Problem: [link]

We can see Newton's third law at work by looking at how people move about. Consider a swimmer pushing off from the side of a pool, as illustrated in Figure 04_04_swimmer. She pushes against the pool wall with

her feet and accelerates in the direction opposite to her push. The wall has thus exerted on the swimmer a force of equal magnitude but in the direction opposite that of her push. You might think that two forces of equal magnitude but that act in opposite directions would cancel, but they do not *because they act on different systems*.

In this case, there are two different systems that we could choose to investigate: the swimmer or the wall. If we choose the swimmer to be the system of interest, as in the figure, then $F_{wall\,on\,feet}$ is an external force on the swimmer and affects her motion. Since acceleration is in the same direction as the net external force, the swimmer moves in the direction of $F_{wall\,on\,feet}$. Since the swimmer is our system (or object of interest) and not the wall, we do not need to consider the force $F_{feet\,on\,wall}$ because it originates *from* the swimmer rather than *acting on* the swimmer. Therefore, $F_{feet\,on\,wall}$ does not directly affect the motion of the system and does not cancel $F_{wall\,on\,feet}$. Note that the swimmer pushes in the direction opposite to the direction in which she wants to move.



A swimmer is exerting a force with her feet on a wall inside a swimming pool

When the swimmer exerts a force $F_{feet\,on\,wall}$ on the wall, she accelerates in the direction opposite to that of her push. This means that the net external force on her is in the direction opposite to $F_{feet\,on\,wall}$. This opposition is the result of Newton's third law of motion, which dictates that the wall exerts a force $F_{wall\,on\,feet}$ on the swimmer that is equal in magnitude but that acts in the direction opposite to the force that the swimmer exerts on the wall.

Other examples of Newton's third law are easy to find. As a teacher paces in front of a blackboard, he exerts a force backward on the floor. The floor exerts a reaction force in the forward direction on the teacher that causes him to accelerate forward. Similarly, a car accelerates because the ground pushes forward on the drive wheels in reaction to the drive wheels pushing backward on the ground. You can see evidence of the wheels pushing backward when tires spin on a gravel road and throw rocks backward.

Another example is the force of a baseball as it makes contact with the bat. Helicopters create lift by pushing air down, creating an upward reaction force. Birds fly by exerting force on air in the direction opposite that in which they wish to fly. For example, the wings of a bird force air downward and backward in order to get lift and move forward. An octopus propels itself forward in the water by ejecting water backward through a funnel in its body, which is similar to how a jet ski is propelled. In these examples, the octopus or jet ski push the water backward, and the water in turn pushes the octopus or jet ski forward.

Applying Newton's Third Law

Forces are classified and given names based on their source, how they are transmitted, or their effects. In previous sections, we discussed the forces called "push," "weight," and "friction." In this section, applying Newton's third law of motion will allows us to explore three more forces: the **normal force**, **tension**, and **thrust**. However, because we haven't yet covered vectors in depth, we'll only consider one-dimensional situations in this chapter. The next chapter will consider forces acting in two dimensions.

The gravitational force (or weight) acts on objects at all times and everywhere on Earth. We know from Newton's second law that a net force

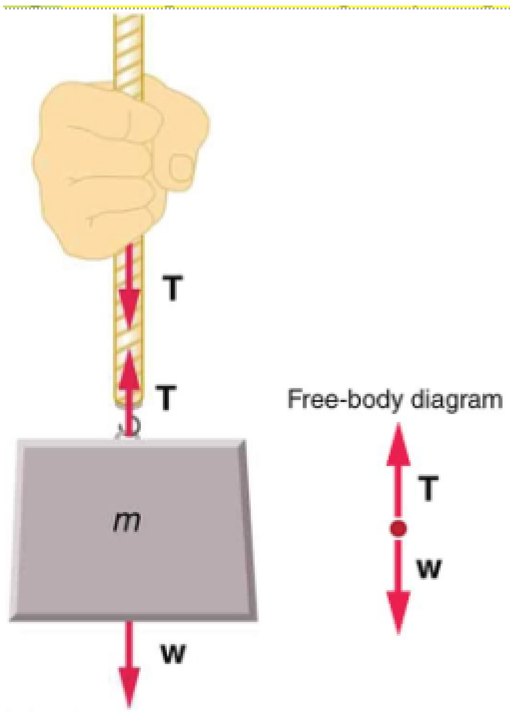
produces an acceleration; so why is everything not in a constant state of freefall toward the center of Earth? The answer is the normal force. The normal force is the force that a surface applies to an object to support the weight of that object; it acts perpendicular to the surface upon which the object rests. If an object on a flat surface is not accelerating, the net external force is zero, and the normal force has the same magnitude as the weight of the system but acts in the opposite direction. In equation form, we write that

Equation:

$$N = mg$$

Note that this equation is only true for a horizontal surface. The word “tension” comes from the Latin word meaning “to stretch.” Tension is the force along the length of a flexible connector, such as a string, rope, chain, or cable. Regardless of the type of connector attached to the object of interest, one must remember that the connector can only pull (or “exert tension”) in the direction parallel to its length. Tension is a pull that acts parallel to the connector, and that acts in opposite directions at the two ends of the connector. This is possible because a flexible connector is simply a long series of action-reaction forces, except at the two ends where outside objects provide one member of the action-reaction forces.

Consider a person holding a mass on a rope as shown in [link].



An object of mass m is attached to a rope and a person is holding the rope.

When a perfectly flexible connector (one requiring no force to bend it) such as an ideal rope transmits a force T, this force must be parallel to the length of the rope, as shown. The pull that such a flexible connector exerts is a tension. Note that the rope pulls with equal magnitude force but in opposite directions on the hand and on the mass (neglecting the weight of the rope). This is an example of Newton’s third law. The rope is the medium that transmits between the two objects forces of equal magnitude but that act in opposite directions.

Tension in the rope must equal the weight of the supported mass, as we can prove by using Newton’s second law. If the 5.00 kg mass in the figure is stationary, then its acceleration is zero, so $F_{net} = 0$. The only external forces acting on the mass are its weight **W** and the tension **T** supplied by the rope. Summing the external forces to find the net force, we obtain

Equation:

$$F_{net} = T - W = 0$$

where T and W are the magnitudes of the tension and weight and their signs indicate direction, with up being positive. By substituting mg for Fnet and rearranging the equation, the tension equals the weight of the supported mass, just as you would expect:

Equation:

$$T = W = mg$$

For a 5.00 kg mass (neglecting the mass of the rope), we see that

Equation:

$$T = mg = \left(5.00\ kg\right)\left(9.80\ m/s^2\right) = 49.0\ N$$

Another example of Newton’s third law in action is thrust. Rockets move forward by expelling gas backward at high velocity. This means that the rocket exerts a large force backward on the gas in the rocket combustion chamber, and the gas in turn exerts a large force forward on the rocket in response. This reaction force is called thrust.

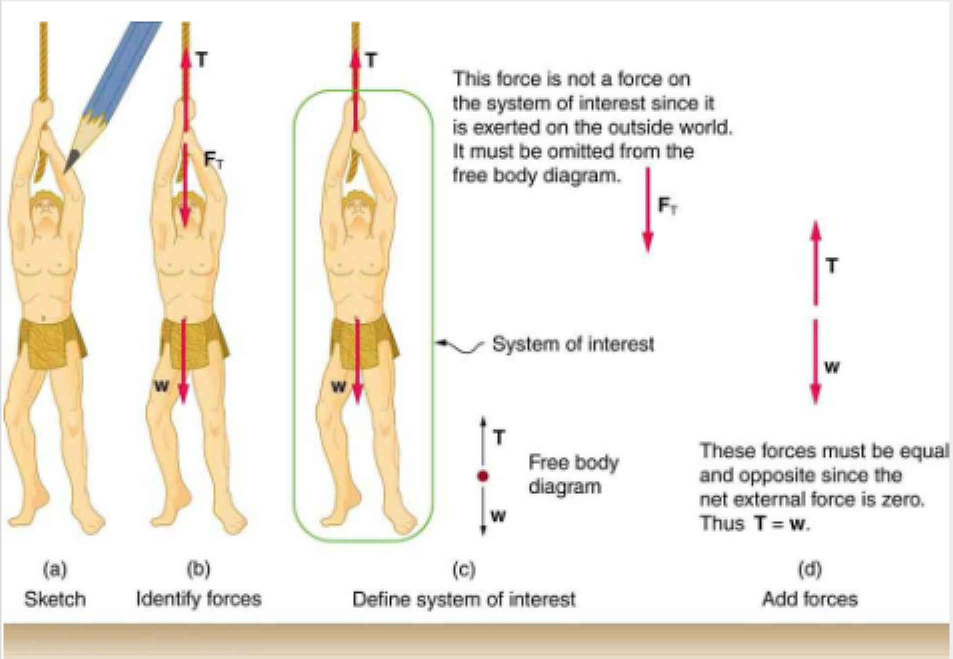
Note: A common misconception is that rockets propel themselves by pushing on the ground or on the air behind them. They actually work better in a vacuum, where they can expel exhaust gases more easily.

Note:

Mathematics: Problem-Solving Strategy for Newton’s Laws of Motion

The basics of problem solving, presented earlier in this text, are followed here with specific strategies for applying Newton’s laws of motion. These techniques also reinforce concepts that are useful in many other areas of physics.

First, identify the physical principles involved. If the problem involves forces, then Newton's laws of motion are involved, and it is important to draw a careful sketch of the situation. Such a sketch is shown in [link](a). Next, as in [link](b), use vectors to represent all forces. Label the forces carefully and make sure that their lengths are proportional to the magnitude of the forces and that the arrows point in the direction in which the forces act.



Next, make a list of "knowns and unknowns" and assign variable names to the quantities given in the problem. Figure out which variables need to be calculated; these are the "unknowns." Now carefully define the system, meaning which objects are of interest for the problem. This decision is important, because Newton's second law involves only external forces. Once the system is identified, it's possible to see which forces are external and which are internal (see [link](c)).

If the system acts on an object outside the system, you then know that the outside object exerts a force of equal magnitude but in the opposite direction on the system.

A diagram showing the system of interest and all the external forces acting on it is called a free-body diagram. Only external forces are shown on free-body diagrams, not acceleration or velocity. [link](d) shows a free-body diagram for the system of interest.

After drawing a free-body diagram, apply Newton's second law to solve the problem. This is done in [link](d) for the case of Tarzan hanging from a

vine. When external forces are clearly identified in the free-body diagram, translate the forces into equation form and solve for the unknowns. Note that forces acting in opposite directions have opposite signs. By convention, forces acting downward or to the left are usually negative.

Unknowns	**Knowns**
Force **a)** Internal **b)** External **c)** Net	Acceleration
Fnet = T-W-02	Tension

This table shows an example of how to make a list of knowns and unknowns.

Exercise:

Problem: [link]

Note:
Newton's Third Law of Motion
https://www.khanacademy.org/embed_video?v=By-ggTfeuJU
This video explains Newton's third law of motion through examples involving push, normal force, and thrust (the force that propels a rocket or a jet). Think about this equation as you watch:
$F_{net} = F_{floor} - f = 150N - 24.0N = 126N$
Words defined in the video:

1. Force
2. Push
3. Normal force
4. Thrust

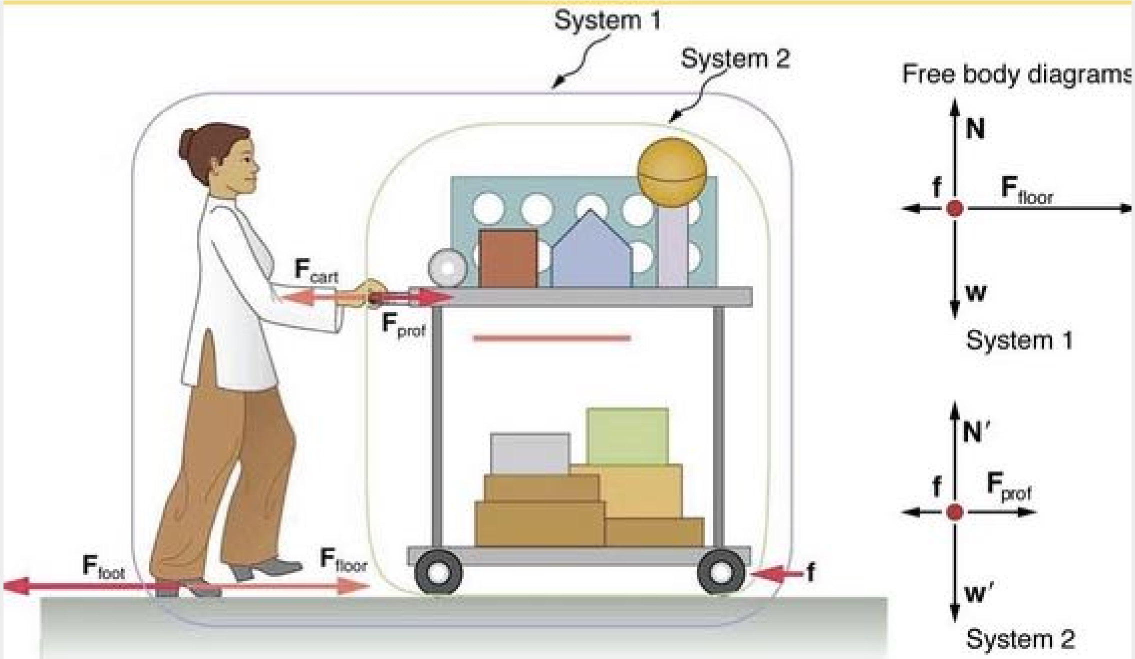
Exercise:

Problem: [link]

Note:
Exercise:
Choosing the Correct System

Problem:

A physics teacher pushes a cart of demonstration equipment to a classroom, as in Image 4.12 Her mass is 65.0 kg, the cart's mass is 12.0 kg, and the equipment's mass is 7.0 kg. To push the cart forward, the teacher's foot applies a force F_{foot} of 150 N in the opposite direction (backward) on the floor. Calculate the acceleration produced by the teacher. The force of friction, which opposes the motion, is 24.0 N.



A teacher pushes a cart of demonstration equipment.

We should not include the forces $F_{teacher}$, F_{cart}, or F_{foot} because these are exerted by the system, not on the system. We find the net external force by adding together the external forces acting on the system (see free-body diagram in the figure) and then use Newton's second law to find the acceleration.

Forces that shouldn't be included:

a. $F_{teacher}$ (m/s^2)
b. F_{cart}
c. F_{foot} ($F_{net} = F_{floor} - f = 150N - 24.0N = 126N$)

Solution:

Newton's second law is $a = \frac{F_{net}}{m}$

The net external force on the system is the sum of the external forces: the force of the floor acting on the teacher, cart, and equipment (in the

horizontal direction) and the force of friction. Because friction acts in the opposite direction, we assign it a negative value. Thus, for the net force, we obtain $F_{net} = F_{floor} - f = 150N - 24.0N = 126N$

The mass of the system is the sum of the mass of the teacher, cart, and equipment: $m = (65.0 + 12.0 + 7.0)kg = 84kg$

Insert these values of net F and m into Newton's second law to obtain the acceleration of the system:

1. $a = \frac{126N}{84kg} = 1.5m/s^2$
    a. F_{net}
        i. equipment
        ii. teacher
        iii. cart
    b. m
    c. F_{floor}
2. $a = \frac{F_{net}}{m}$
3. $a = \frac{126N}{84kg} = 1.5m/s^2$

Discussion

None of the forces between components of the system, such as between the teacher's hands and the cart, contribute to the net external force because they are internal to the system. Another way to look at this is to note that forces between components of a system cancel because they are equal in magnitude and opposite in direction. For example, the force exerted by the teacher on the cart is of equal magnitude but in the opposite direction of the force exerted by the cart on the teacher. In this case both forces act on the same system, so they cancel. Defining the system was crucial to solving this problem.

1. Teacher

a. Exerted by teacher ($1.5 m/s^2$)
b. Exerted on teacher by cart

2. Cart

a. Exerted by cart
b. Exerted by teacher on cart

Section Summary

- Newton’s third law of motion states that, when one body exerts a force on a second body, the first body experiences a force that is equal in magnitude and opposite in direction to the force that it exerts.
- When objects rest on a surface, the surface applies a force on the object that opposes the weight of the object. This force acts perpendicular to the surface and is called the normal force.
- The pulling force that acts along a stretched flexible connector, such as a rope or cable, is called tension. When a rope supports the weight of an object at rest, the tension in the rope is equal to the weight of the object.
- Thrust is a force that pushes an object forward in response to the backward ejection of mass by the object. Rockets and airplanes are pushed forward by thrust.

Key Equations

Equation:

Normal force for a non-accelerating horizontal surface:

$$N = mg$$

Equation:

Tension for an object at rest:

$$T = mg$$

Check Your Understanding

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Concept Items

Exercise:

Problem: [link]

Critical Thinking Items

Exercise:

Problem: [link]

Performance Task

Exercise:

Problem:

To investigate how mass affects tension in a connector, find a rubber band and some objects to hang from the end of the rubber band. How much does the rubber band stretch when a light object is hung from it? How much does it stretch when a heavier object is suspended? What does this show? Measure the mass of the object and the corresponding length of the rubber band in each case and plot a graph of mass vs length. (15 min) [link]

Test Prep Multiple Choice

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Test Prep Short Answer

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Test Prep Extended Response

Exercise:

Problem: [link]

Exercise:

Problem: [link]

Glossary

Newton's third law of motion
: when one body exerts a force on a second body, the first body experiences a force that is equal in magnitude and opposite in direction to the force that it exerts

normal force
: the force that a surface applies to an object; acts perpendicular and away from the surface with which the object is in contact

tension
: a pulling force that acts along a connecting medium, especially a stretched flexible connector, such as a rope or cable; when a rope supports the weight of an object, the force exerted on the object by the rope is called tension

thrust
: a force that pushes an object forward in response to the backward ejection of mass by the object; rockets and airplanes are pushed forward by a thrust reaction force in response to ejecting gases backwards